Planar microfluidic processors

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Abstract— The miniaturization and integration of electronic circuitry has not only made the enormous increase in performance of semiconductor devices possible but also spawned a myriad of new products and applications ranging from a cellular phone to a personal computer. Similarly, the miniaturization and integration of chemical and biological processes will revolutionize life sciences. Drug design and diagnostics in the genomic era require reliable and cost effective high throughput technologies which can be integrated and allow for a massive parallelization. Microfluidics is the core technology to realize such miniaturized laboratories with feature sizes on a submillimeter scale. Here, we report on a novel microfluidic technology meeting the basic requirements for a microfluidic processor analogous to those of its electronic counterpart: Cost effective production, modular design, high speed, scalability and programmability.

I. Introduction

In technical perspective the common handling of liquids is not simply scaleable down to the regime of nano- and picoliters. By using a surface acoustic wave based technology, it is possible to avoid the disadvantages of downscaled pumps and actuate smallest amounts of liquids. In the regime of droplets with $1\mu l$ volume or less the surface tension is the dominant force and represents the droplets beaker, hence no tubes or pipes are necessary. This makes deep etching processes unnecessary for fabricating a SAW device, which can be used to actuate and stir smallest amounts of liquids in a strong controlled way. All the experiments presented here are done with devices that are fabricated only by surface processes. Additionally the functionality of such a device be can easily upgraded by adding analytic and sensor elements for chemical and biological applications.

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II. Mixing

A Rayleigh wave that propagates along a free and smooth surface and hitting a droplet sitting on (s. fig 1), which is loaded on the delay line, couples partly into the droplet as a longitudinal sound wave. This sound wave causes an internal streaming in the fluid. This phenomenon is known as acoustic streaming [1]. We use this effect to stir droplets with a volume between 5 μl and 500 pl.

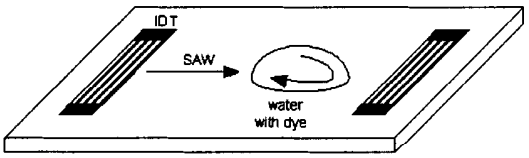

Fig. 1. Setup of the experiment

We used a SAW device with a spilt 4 Interdigital Transducer (IDT) on a 128° rot $LiNbO_3$ substrate. The IDT consisted of twelve pair split 4 finger with 600 μm aperture. The resonant frequencies are 114, 340, 567 and 800 MHz. To visualize the fluid flow a fluorescence dye was dissolved in a water droplet. A RF signal was fed to the IDT. A SAW propagated to the droplet and induced a fluid flow. The fluorescence dye was mixed with the water and excited with the blue light of a GaN-Diode. The mixing was observed with a CCD Camera. To suppress the blue light we used an edge filter, which let pass only the green fluorescence light. With this setup it was possible to observe the mixing of the dye with the water.

The minimum power for an observable fluid flow in our device is -15 dBm. The duration of a mixing experiment depends strongly on the RF power. Increasing the RF power reduces the time for stirring a droplet. At -15 dBm the experiment took some minutes time, at -3.5 dBm the droplet (s. fig. 2) is stirred after 70 s, and at 30 dBm the droplet is stirred after some 10 μs.

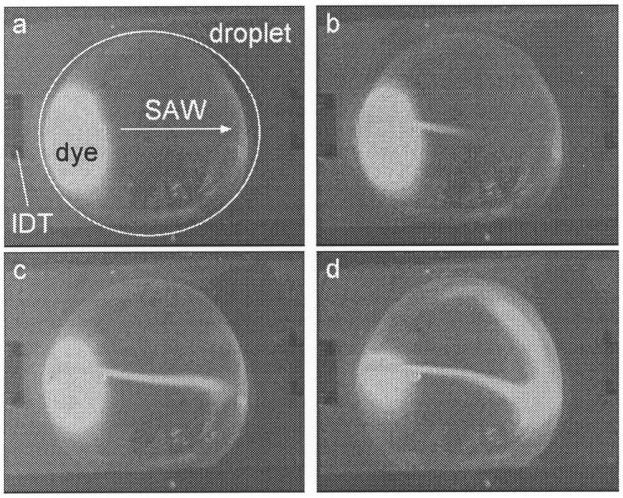

Fig. 2. Illustration of a mixing experiment; the bright spot is the excited fluorescence dye. The droplet has a volume of 5 μl. The figures show an area of 5.4 mm times 4 mm. The black rectangular object on the left is the IDT, the SAW propagates from the left to the right, has a frequency of 114 MHz and -3.5 dBm RF power is fed to the IDT. Figure a) shows the experiments beginning, b) 240 ms after starting mixing, c) after 1 s d) after 5 s.

The SAW frequency is the second important parameter on which the fluid flow depends. Changing the frequency also changes the shape of the fluid flow. Using 340 MHz for mixing instead of 114 MHz only one half of the droplet is stirred (s. fig. 3). To mix a droplet completely the experiment took 2 times longer than at 114 MHz. The two upper frequencies 567 and 800 MHz did not induce any significant mixing. An increase of RF power does not change the shape of the fluid flow at all 4 frequencies.

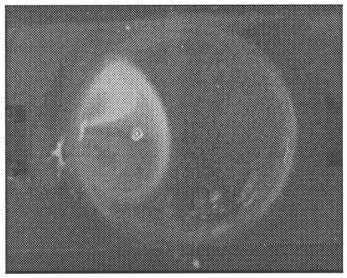

Fig. 3. Shape of the fluid flow in a mixing experiment, the frequency of the SAW is 340 MHz, power P_{SAW}=-3.5 dBm, same setup like in fig. 2; the situation is equivalent to fig. 2 d

Because of the laminarity of streaming in this small volume regime the mixing is not totally homogeneous. In our experiments this can be seen when the droplet is be observed from the side. To improve the mixing process and reach a homogeneous mixing, we used the frequency dependence of the fluid flow. By switching the frequency between 114 and 340 MHz, we were able to mix the droplet quasi chaotically and stir homogeneously, because the laminarity was disturbed by changing the frequency of SAW and thus also the fluid flow. This means that the whole droplet is active mixed.

III. Actuating small droplets

If the whole droplet was in the acoustic path of the device and the RF power was raised over a certain value the droplet began to move [2] in the propagation direction of the SAW. With such a simple setup a droplet can be moved but in almost all experiments the droplet left the delay line in a uncontrolled way. This happened when a part of the droplets wetting line left the sound path. Because of the finite width of the sound path in our delay line the biggest droplets, which could be moved, had a volume of 100 nl.
To guide a droplet so called fluidic tracks (s. fig. 5) were defined on the lithiumniobate surface. For this process the wetting properties of the lithiumniobate were changed by silanization [3, 4, 5]. The original hydrophilic surface became hydrophobic after the silanization process. To define the fluidic tracks the silaniziezed surface was structured with photolithography. The fluidic tracks are two rectangular areas in the center of the delay line. In this areas the original hydrophilic surface was restored by burning out the silan molecules using an oxygen plasma process. The width of the rectangeles was smaller than 30μm. For handling acidic or basic solutions the lithiumniobate surface was layered with 200 nm SiO_2, using a plasma enhanced chemical vapour deposition (PECVD) process. This additional layer shifts the resonance frequency of the device to 114, 340, 564 and 793 MHz. The actuation of a droplet on a layered device does not differ much from a nonlayered one.

To move a droplet a minimum RF power is needed. In our case the minimum power was 18 dBm in continuous wave modus. With this technique we are able to move the droplet over distances with more than 1 cm length without losing control over the droplet. The measured velocities in continuos wave modus was between 0.7 $\frac{mm}{s}$ and 7 $\frac{cm}{s}$. Because of the short duration of one experiment it is not necessary to control the climate conditions to avoid evaporation. Is a droplet moved by a SAW in continuous wave modus, it

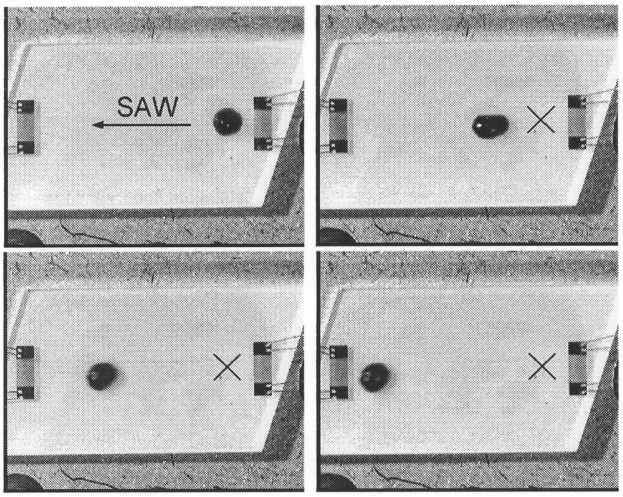

Fig. 4. A droplet is moving from the right to the left, the cross shows the starting position. The droplet consists of a aqueous 1% Bromophenol Blue solution.

always loses some water forming new secondary droplets around. Repeating the experiment with a pulsed RF and constant RF power the droplet moved slower but it did not loose water. The maximum velocity that was reachable without water loss was 1.2 $\frac{cm}{s}$. Changing the puls parameters the velocity was adjustable.
If the droplet was put not centrally onto the fluidic tracks, it hopped centrally into the fluidic tracks, after the SAW began to move the droplet.
The droplet transport like the mixing depends strongly on the SAW frequency. If the frequency is switched from 114 to 340 MHz at constant RF power, the velocity is reduced approximately by a factor of 2. At 564 and 793 MHz transport does not begin as long as the RF power is less then 30 dBm. This result is analogue to the mixing experiments because the internal fluid flow is responsible for the droplet transport. Further more there exists an upper limit for droplet transport. At 114 MHz the droplet will be destroyed, if the RF power is raised over 28 dBm. The droplet is divided into several droplets because the internal fluid flow deforms the droplet dramatically and finally divides it.
The volume of transported droplets was between 1 nl and 100 nl. This shows also indirectly that the same technique can mix droplets with volumes less than 50nl down to 1 nl.

IV. Parallel and serial actuation

Employing this technique for a microfluidic processor we considered also the transport of two droplets.

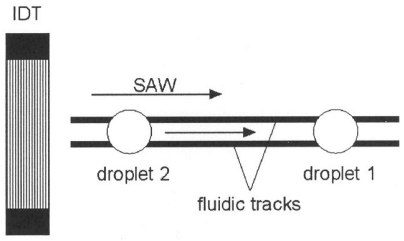

Fig. 5. Two droplets are transported on one fluidic track

At first we did this experiment with serial droplets (s. fig 5). We put one droplet onto the device and positioned it, acoustically driven, 2 mm away from its starting point. Then we put a second droplet onto the device and transported it also acoustically driven. While the second droplet was moved the first one always stayed on his position. The second droplet is moving to the first one until they merge. Finally a unified droplet is moving over the surface.
In this arangement only the droplet, being closer to the IDT, can be actuated. The attenuation by the wetted area has a value of 30 $\frac{dBm}{mm}$ [4]. Fluids attenuates the SAW so strongly that the SAW intensity behind it falls below the threshold for transporting droplets. Hence the second droplet is in the acoustic shadow of the first one.

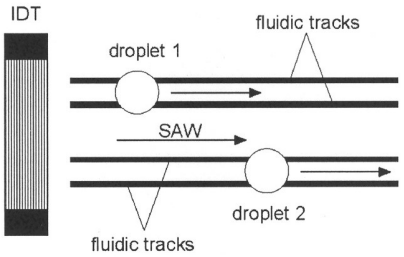

Fig. 6. Droplet transport on two parallel fluidic tracks

To actuate two droplets at the same time using only one acoustic path we realized two parallel fluidic tracks within the same delay line (s. fig. 6). In this configuration the droplets do not shade one another. Both droplets are moved by the same SAW and moved at the same time without perturbation. This shows that it is possible to transport

two or more droplets parallel on a chip with only one acoustic path.
We also realized a chip with a more complex layout, like in fig. 7. On a chip with several delay lines it was possible to actuate two or more droplets at the same time and independent from each other. Also, it was possible to guide a droplet to a crossing delay line and let him switch to it. With such a layout it is possible to move a droplet to every position on a chip.

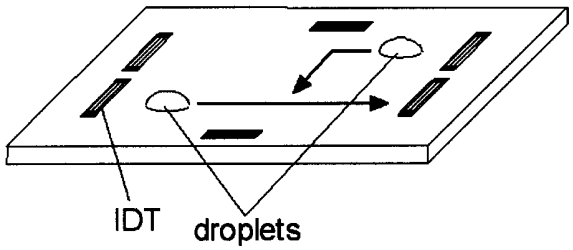

Fig. 7. Transporting two droplets on a chip with 3 acoustic paths

V. Conclusion

We showed that SAW is a powerful technique to realize a microfluidic system. It is possible to actuate smallest amounts of liquid without the need for sophisticated pumps and tubes. The devices can be produced using cheap surface processes similar to those of semiconductor technology. Also it is possible to coat the devices with SiO_2. This enables us to implement all known biological assays, that are developed on glass, on the chip and combine it with the presented technology.

Acknowledgment

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